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RETRIEVAL OF CANOPY STRUCTURE TYPES FOR FOREST CHARACTERIZATION USING MULTI-TEMPORAL AIRBORNE LASER SCANNING

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ABSTRACT

We present a method to characterize forest canopy structure in space and time based on vertical echo distributions from airborne laser scanning (ALS). We developed a transferable, grid-based method using ALS data combined with an automatic determination of the best feasible spatial unit for canopy structure characterization. We derive canopy structure types (CSTs) using a hierarchical, multi-scale classification approach based on Bayesian robust mixture models (BRMMs), which satisfy structurally homogenous criteria without the use of in-situ calibration information. The validation shows promising results for the CSTs, particularly in terms of seasonal and horizontal variations in vertical canopy structure. We conclude that our method can improve the robustness and reliability of canopy structure characterization. Future work will include tests of transferability to a larger variety of forests and extensive testing using CSTs as a structural classification scheme.

***Index Terms* —** ALS, LiDAR, stratification, scale, CST

1. INTRODUCTION

Forests play a pivotal role in linking the global biogeochemical and biogeophysical cycles between the atmosphere and the Earth's surface. In particular the structure of the canopy influences the energy fluxes between the atmosphere and forests can serve as an indicator of a forest stand's resilience and enables an estimation of the stand's potential for conserving biodiversity and the identification of recruitment limitations [1-4]. Airborne laser scanning (ALS) systems are suitable for providing not only horizontal information about the canopy structure, but also detailed vertical information based on the physical measurement principles of active sensing and full-waveform digitization [5].

In our study, an area-based approach (ABA) using regularly spaced grids was used. ABA is flexible in terms of spatial scale analysis and for the better comparison of results. It also allows up- and down-scaling in a robust and transparent manner [6]. Structure variables within a specific grid cell can either be derived from ALS point clouds without using predefined height layers, or can be computed by stratifying the canopy and subsequently evaluating the echo properties within each vertical layer. The derived structure information can include geometric as well as bio-physical variables. The spatial scale at which these variables are extracted is determined by the properties of the ALS and the field reference data, and/or specified according to user requirements. An acceptable compromise often needs to be found between the technical capabilities of ALS and user needs, such as the application domain or cost-benefit considerations [7]. Existing approaches to canopy structure characterization thus often require a large amount of prior information at a pre-defined spatial scale. Furthermore, they usually rely on manual processing steps, which again require prior information about stand characteristics such as tree species, tree age or management type. Therefore, most of these approaches are limited in their transferability to other sites due to necessary local calibration of the applied models, and they tend not to be directly comparable.

To overcome these limitations, we developed a semi-automated, multi-scale and transferable area based approach to provide quantitative descriptions of structurally homogeneous areas we called canopy structure types (CSTs). A CST is a kind of micro-stand, with a unique set of horizontal and vertical canopy structure variables. Previously developed and tested on a small patch (800 ha) of ALS data [8], we transferred the developed method to a much larger scale (180'000 ha) in order to prove the transferability and robustness of the developed approach.

2. STUDY AREA AND DATA

We developed and tested the method at the Laegern, a mainly mixed deciduous mountain forest, in the east of Canton Aargau, Switzerland [9]. The method was subsequently transferred to the entire area of Canton Aargau

(180’000 ha), including areas with different forest management practices and a variety of forest types.

ALS data for the Canton Aargau were acquired by RIEGL’s LMS-Q680i (MILAN Geoservice GmbH) in 2014, under leaf-off and leaf-on conditions. The digital terrain model (DTM) was generated with a spatial resolution of 0.5x0.5 m using the Terrasolid software. A three-dimensional point cloud was obtained composed of planimetric coordinates and ellipsoidal heights. The height above ground was then calculated for each echo of the point cloud by subtracting the interpolated DTM value at the corresponding echo location.

For the entire forested area of Canton Aargau, stand maps were available as a polygon layer. The stand maps were produced by the regional foresters, containing detailed descriptions of the forest type and the forest structure as well as current forest management practices. To ensure the spatial and temporal comparability of the stand maps with the ALS derived canopy structure information, we used only stand polygons updated in the years 2012 – 2014 and selected a representative 100m^2 sample plot within the centre of each polygon, following uniformity criteria.

3. METHOD

One of the essential features of the method is the histogram of the vertical echo heights (percentage of echoes per vertical bin) within a given horizontal grid cell. This histogram can be interpreted as a kind of synthetic waveform reflecting various canopy structure features. The shape of the waveform is affected by many factors, such as the ALS data properties, the underlying grid cell size and the specific canopy structure. Determining the best feasible spatial unit for the histogram calculation is essential as it affects the resulting analysis of the canopy structure characterization. An increase of the grid-cell size will result in more mixing of the horizontal and vertical structure elements within each grid cell [10]. We thus assessed and quantified the sensitivity of ALS-derived structure information in relation to ALS data properties and automatically determined the best feasible spatial units for canopy structure characterization, schematically shown in Figure 1.

To be able to consider the small-scale variability of the vertical canopy structure, we determined a large-scale as well as a fine-scale grid-cell size. We can therefore estimate, if specific features in the histogram derived on a larger grid-cell size are more result of the horizontal scale than representing the actual vertical canopy structure. To determine the CSTs, we applied a hierarchical, multi-scale classification approach. First, we clustered the histograms of the echo heights on the large scale (*clust*), following a Bayesian robust mixture model (BRMM) approach [11]. The clustering itself is based on a fuzzy assignment, i.e., each histogram belongs, with a certain degree of probability, to the respective clusters.

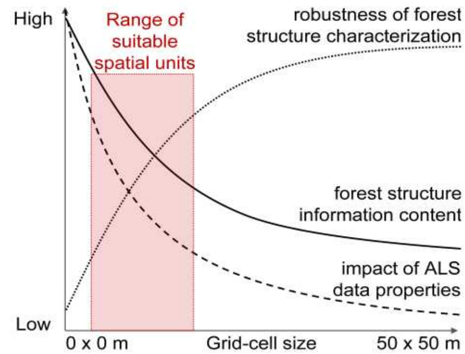

Figure 1: Relationships between ALS data properties, spatial analysis scales and the robustness and content of derived canopy structure information

To verify the consistency of the resulting clusters, we repeatedly sub-sampled the total number of histograms, applied the BRMM and cross-compared the resulting clusters to the clusters based on the clustering of the full number of histograms. Figure 2 shows exemplary two of the resulting clusters with the fuzzy alignment of each histogram according the degree of probability.

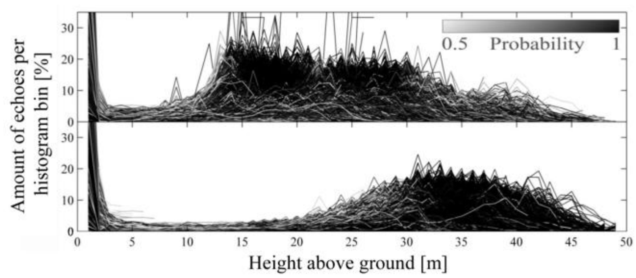

Figure 2: Exemplary results of the BRMM clustering.

In a second step, we calculated the fine-scale histogram variations within each large-scale grid cell ($hist_{var}$) as well as the percentage difference between the canopy returns for the leaf-on and the leaf-off acquisition (c_{diff}), but only canopy returns with an above ground height >3 m were considered. The variables calculated for the fine-scale were subsequently merged with the BRMM clustering results and classified to obtain the final CSTs (*class*) (Figure 3).

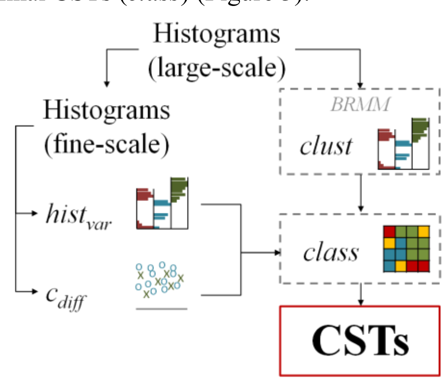

Figure 3: Flowchart of the method to derive the CSTs.

Each of the final CSTs therefore contains information about the vertical structure of the canopy as well as information about the spatial and temporal variability of the canopy structure within each coarse grid cell.

4. RESULTS AND DISCUSSION

The BRMM clustering for the Laegern resulted in 4 separate clusters of histograms. The combination of *clust*, $hist_{var}$ and c_{diff} could lead to 16 possible classes representing the individual CSTs, but only 7 CSTs out of the 16 possibilities occurred (Figure 4).

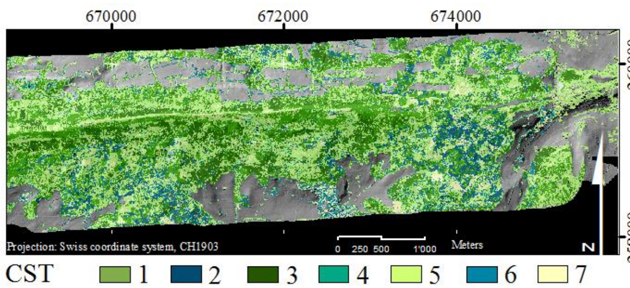

Figure 4: Derived CSTs for the Laegern site.

For Canton Aargau, the BRMM clustering resulted in 7 separate clusters of histograms. Thus, 28 CSTs would have been possible, where at the end 12 CSTs occurred (Figure 5). Each CST was subsequently interpreted and described by forestry experts. For the four largest CSTs in terms of area the description is given in Table 1.

Table 1: Description of the four most prevalent CSTs in terms of area.

CST	Description
1	Deciduous canopy with a long, single canopy layer, no or only a sparse understory, and low horizontal variation of the vertical structure
2	Deciduous canopy with an open, heterogeneous canopy, distinct understory and/or middle canopy layer, and low horizontal variation of the vertical structure
3	Coniferous canopy with a long, single canopy layer, no or only a sparse understory, and low horizontal variation of the vertical structure
4	Deciduous canopy with a heterogeneous canopy, presence of understory, and low horizontal variation of the vertical structure

The validation shows promising results for the determined CSTs, particularly in terms of the seasonal and horizontal variation in the vertical canopy structure.

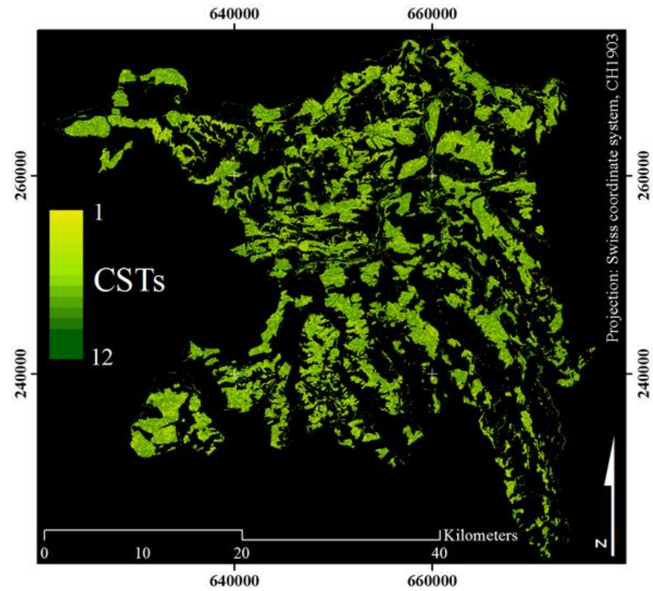

Figure 5: Derived CSTs for Canton Aargau.

The canopy stratification (*clust*) was validated using the stand polygon data on the number and vertical extent of the canopy layers, and shows an overall accuracy of 66.9%. The overall accuracy for $hist_{var}$ was 83%, and in average the classification performs better for evergreen forest stands. The classification into deciduous and evergreen vegetation based on c_{diff} resulted in a high overall accuracy of 91%.

In general, the transition zones between forest and non-forest areas, as well as between the individual CSTs are problematic, as it is always difficult to determine borders of discrete classes while looking at a continuous, natural feature space. The validation of the vertical stratification of the forest canopy showed that the main misclassifications occur either between CSTs that differ only in terms of the canopy length or that are very heterogeneous in their vertical canopy structure. However, assessing the accuracy of the CSTs in terms of the vertical stratification turned out to be very difficult. The forestry experts' subjective visual evaluations of the canopy stratification include a source of error and thus cannot be regarded as an error-free reference, but rather as a source for cross-comparison. Additionally, the canopy stratification approaches used in the forest inventory are more related to the composition of different tree development stages and less focused on the actual vertical foliage distribution. For example, the echoes received from the vegetation in the lower canopy parts can be either from the forest floor, forest succession or caused by low branches of old-growth trees. For the ALS-based canopy stratification, it is not possible to distinguish between these different sources.

For more developed forest stands (mean tree height >30 m), the different forest management strategies are partially reflected in the CSTs. The effect of different forest types (i.e., mixed stands or pure stands) can be seen in the CSTs, mainly with regard to the occurrence and vertical extent of an understory layer.

However, it turns out that: i) only point densities >5 pts/m^2 are appropriate to obtain credible information about the vertical canopy structure as CSTs based on lower densities mainly represent the horizontal variety of canopy heights, ii) the proper interpretation of derived CSTs still requires expert knowledge of forestry as, for example, forests with two canopy layers can mean different things for different forest types (e.g., mixed temperate or tropical forests), and iii) the definition of "heterogeneity" in relation to the horizontal variability of the vertical canopy structure needs to be adopted in accordance with users' requirements.

5. CONCLUSIONS

We conclude that our method substantially improves robustness and reliability of canopy structure retrievals and enables an efficient monitoring of canopy structure. To comply with existing definitions, CSTs can be further specified to take into account additional information, such as pre-defined canopy height classes, or aggregated to spatial scales used in a specific forest inventory system. The canopy structure information contained in the CSTs improves existing structure classification approaches as they provide more detailed information on the canopy stratification, including horizontal variability. For example, even if small-scale variations in the vertical canopy structure affect only small parts of the forested areas, these small patches in the forest are important indicators for assessing functional diversity and habitat differences.

Next steps will include transferability of the CSTs to a variety of open forests, ensuring unambiguous use of the application. Further, we plan to investigate the relationship and usability of CSTs with different established forest ecosystem goods and services, such as diversity, forest stand resistance to disturbances, and stand productivity.

6. ACKNOWLEDGEMENT

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